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Fatigue Performance Of AISI 4340 Steel Ni-Cr-B-Si-Fe HVOF Thermal Spray Coated

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Abstract

Coatings are deposited on high strength materials to improve the surface degradation resistance of several elements. As a consequence, the fatigue strength of coated materials is significantly influenced by internal residual stresses. Despite the fact that hard chromium electroplated is used to guarantee combinations of adhesion, hardness, corrosion and wear resistance, the method decreases the fatigue resistance of aeronautical components due to the high tensile residual stresses and microcracks density contained in the coating.
In order to avoid this problem thermally sprayed HVOF coatings and shot peening process are widely used to improve surface properties of several alloys. The aim of the present study is to analyze the influence of Ni-Cr-B-Si-Fe coating applied by HVOF process on the axial fatigue strength of AISI 4340 steel. The shot peening effect on the fatigue results of coated AISI 4340 steel was also evaluated. The fractured fatigue specimens were investigated using a scanning electron microscope in order to obtain information about the crack initiation points.

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Keywords: Thermal spray coating; fatigue; residual stresses; shot peening; AISI 4340 steel.

1.Introduction

Experimental results have shown that chrome plated specimens have their fatigue resistance reduction associated to residual tensile stresses and microcracks density contained into the coating [1]. It is also well known that chromium plating has adverse health and negative environmental effects [2]. Although the problems already mentioned, chromium plating is used to guarantee combinations of adhesion, hardness, corrosion and wear resistance [3]. The microcracks density contained in two kinds of hard chromium plating: one called "accelerated" (high velocity of deposition and fluoride free) and other conventional, were associated to fatigue, wear and corrosion behavior of coated AISI 4340 steel [4]. Bifurcation in the crack tip and deviation during growth close to the interface in multilayer systems of coatings, are considered to be responsible for increase in fatigue strength. Electroless nickel interlayer was capable to retain crack propagation from hard chromium external layer [5]. The replacement of chromium plating by thermally sprayed HVOF coatings is considered to be a possible alternative, as a result of experimental information obtained (6-8). Shot peening process is widely used to increase the fatigue strength of hard chromium electroplated specimens.

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Comparison between the axial fatigue strength of AISI 4340 steel hard chromium electroplated and WC-17% Co HP/HVOF thermal spray coated, showed better performance for the latter. It was also observed that the shot peening process restored the fatigue life of AISI 4340, WC-10Co-4Cr thermal spray coated (6).

Fatigue, wear and corrosion resistance were also studied for AISI 4340 steel, WC-12Co HVOF thermal spray coated (3). Results showed that the tungsten carbide thermal spray coating decreased the axial and rotating bending fatigue strength of AISI 4340 steel. A performance even worse was obtained with hard chromium electroplating. High compressive residual stresses were observed inside thermal spray coating and at interface coating/substrate. One way to improve the fatigue resistance is by using shot peening process. The intensity influences the residual stress values as well as the width of field generated (9).

The shot peening process was also characterized as an efficient method to increase the fatigue strength of hard chromium electroplated specimens (10).

The influence of $Cr_3 C_2$-25NiCr and WC-20Ni coatings applied by HVOF and chromium electroplating on fatigue strength , abrasive wear and corrosion resistance of AISI 4340 steel 39HRc was evaluated (11). S-N curves showed higher axial fatigue resistance for HVOF coated specimens in comparison to electroplated chromium. On the other hand, thermally sprayed Cr_3C_2-25NiCr showed lower fatigue life compared to base material. Similar behavior was observed for thermal spray coated WC-10Ni. For both thermal spray coatings compressive residual stresses at interface coating/substrate were observed.

The effects of Ni-Cr-B-Si-Fe HVOF thermal spray coating and hard chromium electroplated on the axial fatigue strength of AISI 4340 steel is evaluated in this research. Scanning electron microscopy was used to study fatigue source appearance, thickness and coating adhesion.

2. Experimental Details

2.1 Material and Mechanical Properties

The chemical composition of the tested AISI 4340 steel, 0.42 C; 0,63 Mn; 0.83 Cr; 1.80 Ni; 0.22 Mo; 0.19 Si; 0.008 S; 0.015 P (Wt%), is in accordance to standard AMS 6414.

The heat treatment was performed according to standard MIL-H-6875. To obtain the desired mechanical properties, steel samples were quenched from 830ºC during 45 minutes, cooled in oil (20ºC) followed by double tempering process in the range 230 ± 5ºC for 4 hours.

Mechanical properties are: hardness 52 HRc, ultimate tensile strength 1950 MPa, yield strength (0,2%) 1515 MPa, elongation 10%.

2.2 Axial Fatigue Tests

The axial fatigue test specimens were prepared according to ASTM E 466.

Surface roughness measurements were carried out in the reduced section of the specimen. Average Ra value was 2.75µm and standard deviation 0.89µm. After machining, specimens were submitted to stress relief heat treatment at 190ºC for 04 hours. The substrate was grit blasted using Al_2O_3 with a particle size of 90 mesh. The blasting process is an important procedure to guarantee a high quality surface condition for coating deposition.

Fatigue tests were conducted with constant amplitude simusoidal loading, stress ratio R=0.1, frequency of 10Hz at room temperature. Experimental tests consider as fatigue strength the complete fracture of specimen or 10^6 load cycles. To obtain the axial S-N curves, five groups of fatigue specimens were prepared and tested. The sample size was 12 for each material condition.

.24 smooth specimens of AISI 4340 steel,

.12 smooth specimens of AISI 4340 steel, shot peened,

.12 smooth specimens of AISI 4340 steel shot peened and hard chromium electroplated, 250µm thick,

.12 smooth specimens of AISI 4340 steel, Ni-Cr-B-Si-Fe thermal spray coated by HVOF process, 250µm thick.

.12 smooth specimens of AISI 4340 steel shot peened and Ni-Cr-B-Si-Fe thermal spray coated by HVOF process, 250µm thick.

2.3 Hard Chromium Electroplating

The hard chromium electroplating was carried out by chromic acid solution with 250g/l of CrO_3 and 2.5g/l of H_2SO_4 ,at 50ºC - 55ºC, with a current density from 31 A/dm^{2,} and speed of deposition equal to 25µm/h. A bath with a single catalyst based sulphate was used. After the coating deposition, specimens were subjected to a hydrogen embrittlement relief treatment at 190ºC for 08 hours. Average surface roughness of the hard chromium electroplating was Ra $\approx$ 3,13μm in the reduced section and standard deviation 0.79μm, in the plated condition.

2.4 HVOF Thermal Spray Process

The chemical composition of the coating Ni-Cr-B-Si-Fe used in this research was: 14.5% Cr; 4.5% Fe; 4.5% Si; 3.2% B, Ni balance. Characteristics are: resistance to corrosion and wear, can be used until 815ºC and low hardness compared to WC-Co.
Coatings were deposited by HVOF torch, model JP-5000, TAFA 1310 VM Technologies. Coating thickness was approximately 250μm with surface roughness equal to Ra = 2,7μm. Spraying parameters are as follow:
Process: TAFA JP-5000; Oxygen pressure: 9.4-10.1 bar (136-146psi); Fuel: Querosene; Fuel pressure: 7.8-8.6 bar (114-124psi); Powder Supply Pressure: 0.2-0.4 bar (3-6 psi); Spray distance: 300mm; Maximum substrate temperature: 170ºC.

2.5 Residual Stress Measurement

The X-ray diffraction method was used to determine residual stresses induced by hard chromium electroplated and thermal spray coating. The accuracy of the stress measurement was ±20MPa. To obtain the stress profile as function of depth, layers were removed by electrolytic polishing with non-acide solution.

2.6 Shot Peening

The shot peening process was performed according to standard SAE-AMS-S- 13165 . Treated specimens resulted in surface roughness equal to 1.08± 0.14μm. The shot peening occured before grit blasting with aluminum oxide in samples coated by HVOF.
The shot peening parameters used were:
Intensity: 0.006 - 0.0010A; S 230 steel shot; Output flux: 3kg ; Velocity: 250mm/min; Distance> 200mm; Rotation 30rpm; 120% coverage
The intensity 0.008A was used according to rotating bending fatigue results obtained for AISI 4340 steel, 50HRc [7].

3 - Results and Discussion

The coating hardness was determined with a microhardness testing system using a Vickers diamond indenter on the top surface of polished cross sections and represented in figure 1.

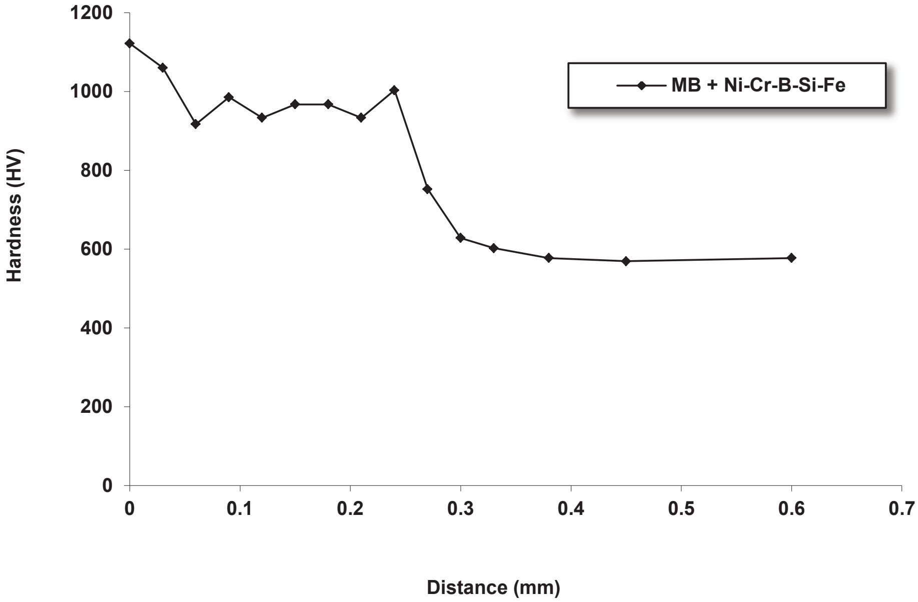

Fig. 1. Vickers Microhardess .100g . Ni-Cr-B-Si-Fe

To perform the indentation, a load of 100g was used and maintained for 15s. At the interface coating /substrate , the increase in hardness is associated to the work hardening effects, which resulted from the fact that specimens HVOF thermal spray coated were blasted to enhance adhesion. The through-thickness Vickers microhardness variation of electroplated chromium coating, according to figure 2 is: surface 897, core 906; interface 912.

Tensile residual stresses resulted for AISI 4340 steel at surface and 0,10mm from the surface, + 150MPa and + 75MPa, respectively. After the shot peening process, compressive residual stresses are observed on surface, -330MPa. The residual stress profile shows compressive stress at 0,10mm depth, -630MPa and tendency to decrease in value with increase in depth (-170MPa at 0.20μm). These results agree with those obtained by [9], in which the influence of four shot peening conditions on the rotating bending fatigue tests were analysed.

The HVOF thermal spray process reduced the tensile residual stress on the specimen surface, (+150MPa) to +125MPa at interface coating/substrate. At 0.10mm and 0.20mm from interface coating/substrate, tensile residual stresses are +50MPa, respectively. Compressive residual stresses are formed from mechanical deformation during particle impact. The tensile shrinkage stresses of the coating are associated to the fast cooling and solidification as particle strike the surface. The through - thickness residual stress for shot peened AISI 4340 steel Ni-Cr-B-Si-Fe thermal spray coated assumes -370MPa at interface coating-substrate and remained compressive until 0.10mm depth, -30MPa.

Figure 2 shows axial fatigue S-N curves for AISI 4340 steel, Ni-Cr-B-Si-Fe HVOF thermal spray coated. Base material hard chromium electroplated and the shot peened condition were used for comparison. In table 1 numerical data is presented to understand results obtained.

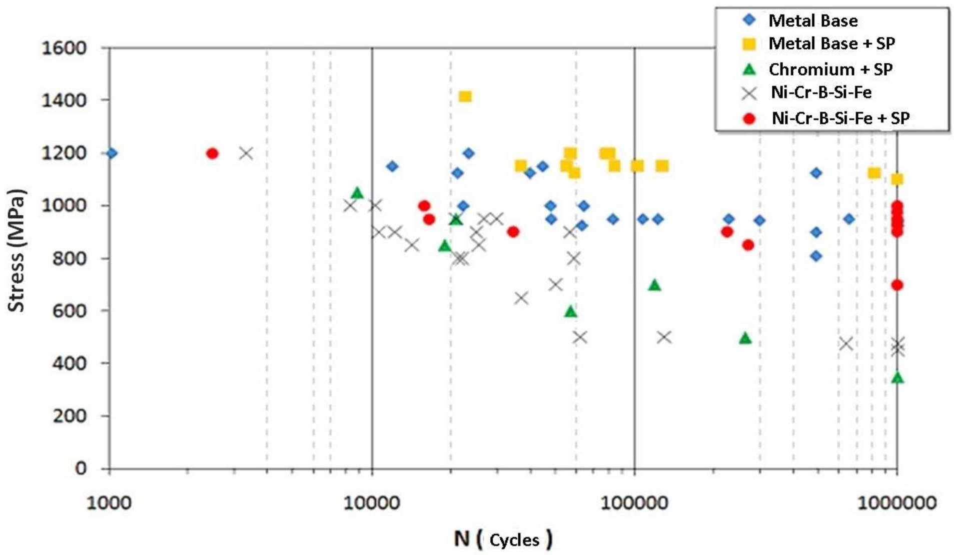

Fig. 2. Axial S-N Curves. AISI 4340 steel. Ni-Cr-B-Si-Fe HVOF thermal spray coated.

Table 1. AISI 4340 steel. Number of cycles to failure.

	N1	N2	N9	N10	(%)	(%)	(%)	(%)	(%)
Cycles / Stress (MPa)	4340	4340+ shot peening	4340+ Ni-Cr-B-Si-Fe	4340+shot peening + Ni-Cr-B-Si-Fe	N2/N1	N10/N9	N9/N1	N10/N2	N10/N1
1.200	23337	71747	3330	2486	+207	-25,4	-85,8	-96,5	-89,4
1150	28316	92175	-	-	+225	-	-	-	-
1125	30557	812825	-	-	+2560	-	-	-	-
1.100	-	10^6	-	-	-	-	-	-	-
1.000	44698	-	9314	15907	-	+70,7	-80,2	-98,5	-64,5
950	206975	-	25848	508276	-	+1866	-87,5	-	+145
945	298715	-	-	-	-	-	-	-	-
935	10^6	-	-	-	-	-	-	-	-
900	-	-	26234	420057	-	+1501	-97,4	-	-
850	-	-	19884	271449	-	+1265	-	-	-
800	-	-	34054	-	-	-	-	-	-
700			50185	10^6					
500			95739						
450			10^6						

Analysis of data from figure 2 revealed the decrease in axial fatigue strength of AISI 4340 steel associated with chromium coating. High tensile internal residual stresses, microcracks density and strong adhesion coating/substrate interface are responsible for the reduction in fatigue life of chromium coated specimens [12]. The shot peening process was applied before electroplating. Shot peened base material showed higher strength in comparison to AISI 4340 steel. In table 1, the ratio N2/N1 indicates increase in the shot peening effect, with decrease in applied maximum stress. According to experimental data from figure 2, thermal spray coated material with Ni-Cr-B-Si-Fe showed lower axial fatigue strength than AISI 4340 steel. The ratio N9/N1 confirms the influence of the thermal spray coating for low and high cycle fatigue. The shot peening process increased the NI-Cr-B-Si-Fe thermal spray coated axial fatigue life, according to Figure 2 and ratio N10/N9 in table 1, but still lower than SxN data for base material, ratio N10/N1.

Figure 2 indicates that Ni-Cr-B-Si-Fe thermal spray coating applied by HVOF process, can be considered as an alternative for chromium plating, despite the fact that in both cases a reduction effect on the axial fatigue strength of AISI 4340 steel was observed. The shot peening prior to thermal spraying showed to be an excellent alternative to increase fatigue strength of coated AISI 4340 steel. It is important to consider, the compressive residual stresses at surface (-330MPa), 0,10mm from surface (-630MPa) and 0.20mm depth (-170MPa), obtained in shot peened AISI 4340 steel specimens. Compressive residual stresses are also present in shot peened base material, Ni-Cr-B-Si-Fe HVOF thermal spray coated, at interface coating/substrate and at 0,10mm from interface. Fracture surface analysis in figure 3, from axial fatigue specimen Ni-Cr-B-Si-Fe HVOF thermal spray coated, indicate that preferential crack growth occurs at the coating/substrate interface, leading to adherence fracture and possible delamination**.**

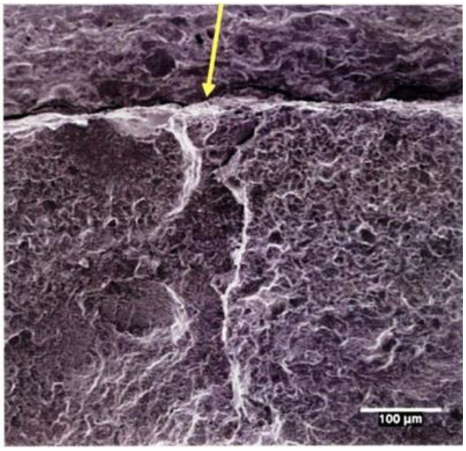

Fig. 3. Fracture surface. AISI 4340. steel Ni-Cr-B-Si-Fe HVOF thermal spray coated.

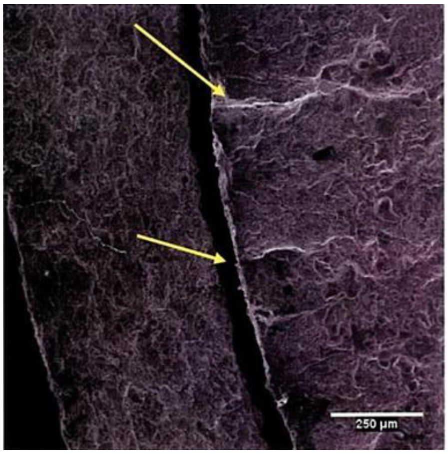

Fig. 4. Fracture surface AISI 4340 steel shot peened. Ni-Cr-B-Si-Fe HVOF thermal spray coated.

The coating delamination at the substrate interface, in different solid materials, may be correlated to the direction in which the crack approaches the interface and the condition of the materials involved, ductile/brittle or vice-versa. The reduction in fatigue strength of AISI 4340 steel coated with Ni-Cr-B-Si-Fe, despite compressive internal residual stresses induced by the thermal spray process, may be explained by the presence of high density of porous and oxide inclusions into coating, that commonly forms during the process. Another important parameter to be considered is the coating thickness, which is approximately 250µm.

Figure 4 shows an axial fatigue fracture surface from AISI 4340 steel shot peened and Ni-Cr-B-Si-Fe thermal spray coated.

The shot peening process delays fatigue crack propagation inside substrate. Fatigue cracks growth at interface coating/substrate and delamination are also observed.

4. Conclusions

- Experimental results indicate decrease in axial fatigue strength of AISI 4340 steel shot peened and chromium electroplated.
- Shot peened AISI 4340 steel showed better fatigue performance in comparison to base material.High compressive residual stresses were present at surface and subsurface.
- HVOF thermal spray coated material with Ni-Cr-B-Si-Fe showed lower axial fatigue strength in comparison to AISI 4340 steel. The shot peening process increased fatigue life, but SxN data indicate values lower than base material.
- For Ni-Cr-B-Si-Fe, in the shot peening condition, compressive residual stress at interface coating substrate is -370MPa.
- Fracture surface analysis indicate that the shot peening process pushes the crack source beneath the surface, due to the compressive residual stresses involved. Crack growth at interface coating/substrate and coating delamination were also observed.
- The reduction in axial fatigue strength of coated steel may also be attributed to the presence of high density of porous and oxide inclusions.

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References

1. H.J.C. Voorwald, R. Padilha, M.Y.P. Costa, W.L. Pigatin, M.O.H. Cioffi (2007). Effect of electroless nickel interlayer on the fatigue strength of chromium electroplated AISI 4340 steel. Int. J. Fatigue 29, 695-704.
2. J.A. Picas, A.Forn, G. Matthäus, Wear 261 (2006), 477.
3. M.P. Nascimento, R.C. Souza, I.M. Miguel, W.L. Pigatin, H.J.C. Voorwald, Effects of tungsten carbide thermal spray coatings by HP/HVOF and hard chromium electroplating on AISI 4340 high strength steel. Surface Coatings Technology 138 (2001), 113-124
4. M.P. Nascimento, L.R.O. Hein, H.J.C. Voorwald, Microcracks density in hard chromium electroplating measured by Stereology Tecnhique. Ata Microscopica, volume 9, number2, December 2000, pp.1-5.
5. M.P. Nascimento, M.A.S Torres, R.C. Souza, H.J.C. Voorwald, Effect of a shot peening pre-treatment on the fatigue behavior of hard chromium in electroless nickel interlayer coated AISI 4340 aeronautical steel materials research, Vol.5, nº2, 95-100, 2002.
6. H.J.C. Voorwald, R.C. Souza, W.L. Pigatin, M.O.H. Cioffi, Evaluation of WC-17Co and WC-10Co-4Cr thermal spray coatings by HVOF on the fatigue and corrosion strength of AISI 4340 steel. Surface Coatings Technology 190 (2005), 155-164.
7. R.C. Souza, M.P. Nascimento, H.J.C. Voorwald, W.L. Pigatin, The effect of WC-17Co thermal spray coating by HVOF and hard chromium electroplating on the fatigue life abrasive wear resistance of AISI 4340 high strength steel, Corrosion Reviews, Vol.21, nº1, 2003,75-96.
8. R.C. Souza, H.J.C. Voorwald, M.O.H. Cioffi, Fatigue strength of HVOF sprayed Cr_3C_2 - 25NiCr and WC-10Ni on AISI 4340 steel, Surface & Coatings Tecnhology 203(2008), 191-198.
9. M.A.S. Torres, H.J.C. Voorwald, An evaluation of the shot peening, residual stress relaxation on the fatigue life of AISI 4340 steel. International Journal of Fatigue, 24 (2002), 877-866.
10. M.P. Nascimento, R.C. Souza, W.L. Pigatin, H.J.C. Voorwarld, Effects of surface treatments on the fatigue strength of AISI 4340 aeronautical steel. International Journal of Fatigue, 23 (2001), 607-618.
11. R.C. Souza, H.J.C. Voorwald, M.O. H. Cioffi, fatigue strength of HVOF sprayed Cr_3C_2-25NiCr and WC-10Ni on AISI 4340 steel, Surface & Coatings Technology, 203 (2008), 191-198.
12. H.J.C. Voorwald, M.P.Silva, M. Y.P.Costa and M.O.H. Cioffi, Improvement in the fatigue strength of chromium electroplated AISI4340 steel by shot peening. Fatigue & Fracture of Engineering Materials & Structure, 32 (2) (2009) 97-104.